

Walking and Running with Star^{LE}TH

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This paper presents the latest advances we made in static and dynamic locomotion with our compliant quadrupedal robot Star^{LE}TH. It summarizes the robot design and outlines the different underlying control principles used to achieve sophisticated locomotion performance. The focus of the paper is put on experimental findings which illustrate that the applied actuation and control principles are a valuable approach to bring our robotic devices a step closer to their natural counterparts.

1 Motivation

Legged robotic devices, and in particular quadrupedal systems, have made significant progress in the past years. Such artificial systems have broken records in different areas. For example, Boston Dynamic’s hydraulically actuated Cheetah [4] very recently set the world record in fast running. Last year, the Cornell Ranger [1] was able to walk the Marathon with a cost of transport that is better than a human. This high energetic efficiency was achieved as the robot largely exploits swing leg pendulum dynamics similar to McGeer’s passive dynamic walkers [13]. Going a bit further back in the history of quadrupedal locomotion, different groups participating in the LittleDog challenge (e.g. [11]) pushed the state of the art of climbing in very rough and unstructured terrain using precise foot placement strategies. The large range of motion due to the mechanical design of the robot and advanced motion planning, control and learning algorithms led to remarkable performances of the robots. Other robots like the six-legged robot RHex [12] are able to overcome similar obstacles in a brute force way owing to the inherent robustness of the system design.

Despite these advances in design and control, all existing robotic solutions are still far behind our natural counterparts. Unlike animals and humans, most of the robots lack some of the key characteristics, namely *versatility*, *speed*, *efficiency*, and *robustness*. Vertebrates are able to climb in very difficult environment by carefully selecting the footholds, at the same time they can walk or run nearly effortlessly on less challenging ground while maintaining balance even in case of large external disturbances. On the contrary, man-made machines as previously mentioned are particularly good in

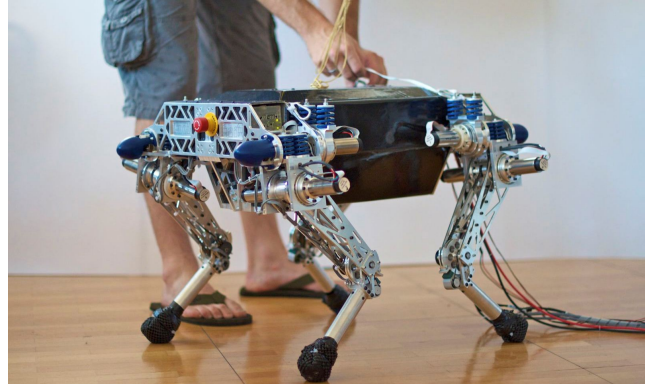


Figure 1: Star^{LE}TH: A compliant quadruped robot.

a specific domain, but perform poorly regarding at least to one of the other aforementioned key features.

At the Autonomous Systems Lab, we recently developed the quadrupedal robot Star^{LE}TH that combines all these features and allows us to investigate different control and planning principles to achieve advanced locomotion skills. In the following section we give an overview of the applied design and actuation principles, followed by an outline of the locomotion control methods. In the experimental part, we illustrate how the robot can statically walk while optimizing energetic efficiency or safety against slippage. We present results of a dynamic trotting gait under substantial external disturbances and summarize some interesting aspects from a bio-mechanical point of view.

2 System Design

Star^{LE}TH (Springy Tetrapod with Articulated Robotic Legs) is a fully actuated robot that features four identical, completely symmetric articulated legs connected to a single rigid main body. Each leg has three degrees of freedom (DOF) that are arranged in mammalian-style with successive hip abduction/adduction, hip flexion/extension, and knee flexion/extension. To achieve fast swing leg motion, we put emphasis on a lightweight construction with all actuators tightly integrated at the main body. Using rotational actuators in all joints makes a large range of motion possible, so that the leg can be fully retracted and extended. Having a body length of about 0.5 m, segment lengths of 0.2 m, and a total weight of 23 kg,

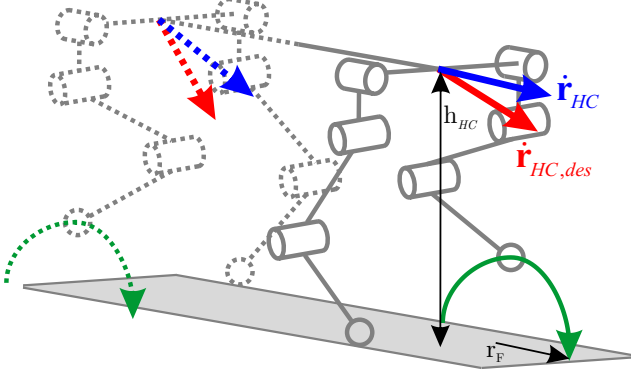


Figure 2: Foothold planning in a dynamic gait.

this robot is comparable to a medium-sized dog.

StarLETH is driven by highly compliant series elastic actuators which have very similar properties of our muscles and tendons. They act as compliant elements to temporarily store a large amount of energy. Mechanical springs decouple the motor and gearbox from the joint to protect the gearbox from impact loads at landing, to intermittently store energy, and most importantly, to allow for high fidelity joint torque control. This opens a very broad spectrum of opportunities to implement novel locomotion control algorithms.

The system is equipped with an inertial measurement unit (IMU) that allows, in combination with the accurate kinematic information from the joint encoders, to precisely estimate the state of the robot [3]. Hence, all maneuvers can be executed without additional perception or using a motion capture system. Differential pressure sensors in the compliant ball feet give reliable feedback about the contact situation of the legs. StarLETH is operated on a large-scale custom made treadmill with the dimensions of about 2.90 m × 1.6 m in most of the experiments presented in this paper.

3 Control Design

We separate locomotion control into three layers such as *motion generation*, *motion control*, and *actuator control*.

3.1 Motion Generation

Motion generation defines the desired foot locations and the motion of the main body. For static walking in rough terrain, such as in the LittleDog challenge (e.g. [11]), the motion of the robot is mainly determined by the available footholds. As soon as it comes to less demanding surfaces, the robot can speed up and switch to dynamic gaits. In that case the desired foothold locations are determined by the desired body velocity as well as the postural control strategy to counteract external disturbances. Following the fundamental principles that can be adopted from the SLIP template [2] respectively the early Raibert controllers [14], we apply

the control framework described in [6]. A predefined gait graph clocks the swing and stance phases of each leg and specifies the foot fall pattern. The stepping position of each leg is computed based on the reference frames in the middle of the front and back leg pair, respectively, as shown in Figure 2. The desired position of the foot is calculated relative to the nominal standing position by

$$\mathbf{r}_F = \frac{1}{2} \dot{\mathbf{r}}_{HC,des} T_{st} + k_R^{FB} (\dot{\mathbf{r}}_{HC,des} - \dot{\mathbf{r}}_{HC}) \sqrt{h_{HC}}, \quad (1)$$

with the velocity at the respective hip center $\dot{\mathbf{r}}_{HC}$, the stance duration T_{st} defined by the gait pattern, the hip height h_{HC} to normalize the feedback contribution [17], and the feedback control gain k_R^{FB} .

3.2 Motion Control

To achieve robust and sophisticated walking, we use a hierarchical task space inverse dynamics control framework [9] that is based on support consistent equations of motion and prioritized least square optimization. The complex behavior of a robotic system evolves from the simultaneous execution of different motion tasks, such as ensuring stability, moving a foot point, or keeping certain posture. At the same time, joint torques and ground contact forces can be optimally distributed, e.g. to guarantee safety against slippage or to minimize the actuator effort. The hierarchical task decomposition ensures that critical tasks are fulfilled by all means while less important ones are only fulfilled as good as possible.

3.3 Actuator Control

We developed two complementary actuator control strategies for torque and position control [10]. To achieve high energetic efficiency and accurate torque control, we designed the mechanical damping in the actuator as low as possible. In return, to achieve fast and precise foot positioning and to suppress undesired oscillations due to the series elasticity, we implemented a position controller that can actively damp out all undesired oscillations.

4 Results

Preliminary performance tests with StarLETH showed a payload capability¹ of 25 kg and a large, passive robustness² against impacts during dynamics maneuvers [8].

4.1 Static Walking

Static walking gaits are used for slow locomotion speed and in particular when it comes to crossing challenging terrain. Static stability can be ensured since at least three legs are in contact with the ground. Moreover, this offers the potential to optimize the contact forces and joint torque distribution, respectively.

¹<http://www.youtube.com/watch?v=ZEZe2w1NUGo>

²<http://www.youtube.com/watch?v=5XLf43GXFxI>

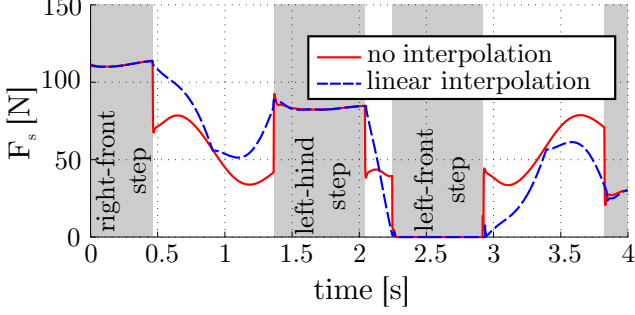


Figure 3: Smooth contact force distribution is achieved by interpolating between subsequent contact situations.

In a first set of experiments, we compared actuator efficiency defined by³

$$E_\tau = \int \tau^T \tau dt, \quad (2)$$

and risk of slippage expressed by the relation between local tangential and normal contact forces:

$$\bar{\mu} = \text{mean} \left(\frac{F_{\text{tangential}}(t)}{F_{\text{normal}}(t)} \right). \quad (3)$$

By minimizing the local tangential forces in contrast to optimizing actuator efficiency, we could lower $\bar{\mu}$ from 0.2 to 0.04. In return, the actuator cost E_τ was increased by about 20% while the executed motion remained exactly equal.

Legged locomotion is accompanied by discrete changes in the contact situation which is often reflected in discontinuous actuator torques and contact force distributions. To compensate for that, we apply an interpolation method between two subsequent contact situation by changing the internal force directions as illustrated in Figure 3.

As soon as it comes to challenging terrain, it is often required to perform climbing maneuvers by clinging to the ground. In case the local contact surface normal directions are known, the proposed optimization routines allow to minimize the local tangential forces and hence to minimize the risk of slippage⁴. We demonstrated this capability by walking on a curved surface shown in Figure 4.

4.2 Dynamic Trotting

Dynamic locomotion is characterized by inherent instability as the robot will fall if the legs are not appropriately positioned. When performing such a gait, the robot can resist external disturbances in two ways. First, it can produce reaction forces with the grounded legs to counteract the perturbations as good as possible. Second, to compensate for disturbances in the

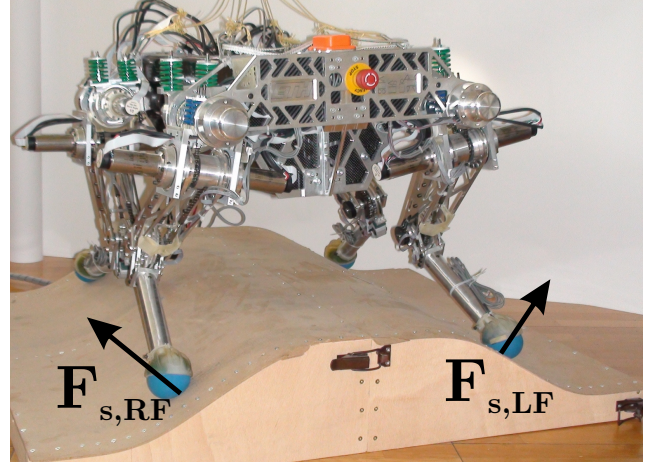


Figure 4: Robust walking on a curved surface is only possible by applying internal contact forces.

underactuated subspace⁵, the subsequent foothold locations of the current swing legs are adapted appropriately. To evaluate the performance of our control approach for dynamic gaits, we performed two experiments with StarLETH trotting at speed in the range of 0.5–0.7 m/s on the treadmill. In the first one, we put unperceived obstacles on the treadmill as shown in Figure 5(a). The robot detects the change in ground elevation by the tactile sensor in the foot element and reacts accordingly⁶. In the second experiment, we kicked the robot from the side while the quadruped was trotting (Figure 5(b)). The robot immediately steps sideways to counterbalance this impulsive disturbance, and finds back to the nominal trotting gait⁷ within two steps.

In order to quantify the energy consumption we conducted a long-term experiment by letting StarLETH trot a distance of 100 m at constant speed. To get comparable values to the metabolic costs found in nature, we measured the electric power delivered at the socket before the AC/DC converter. For a trotting gait with ≈ 0.43 m/s, the robot required an average power of $P_{el} = 360$ W. This results in a dimensionless cost of transport (COT) of about 3.5. The energy losses of all electric components without load amounts to $P_{loss0} \approx 80$ W. We estimated an average positive mechanical power $P_{mech_{pos}} \approx 32$ W by multiplying joint torque with motor speed. This means on one hand that the mechanical COT including all control actions required to stabilize the robot on its nominal walking gait is $COT_{mech_{pos}} = 0.28$. On the other hand, we notice that the efficiency of the overall energy conversion is as low as about 10%. This is reasonable as already the maximal possible efficiency is not more than 55%, which is determined by multiplying the values given by the manufacturer for AC/DC converter ($\eta_{AC/DC} = 90\%$),

³ τ^2 is often used to quantify electric losses in the motor

⁴http://www.youtube.com/watch?v=_OfJoyeveA4

⁵for trotting this is the rotation around the line of support

⁶<http://www.youtube.com/watch?v=Wuc7mL0hkGo>

⁷<http://www.youtube.com/watch?v=7F6GRFPkdp0>

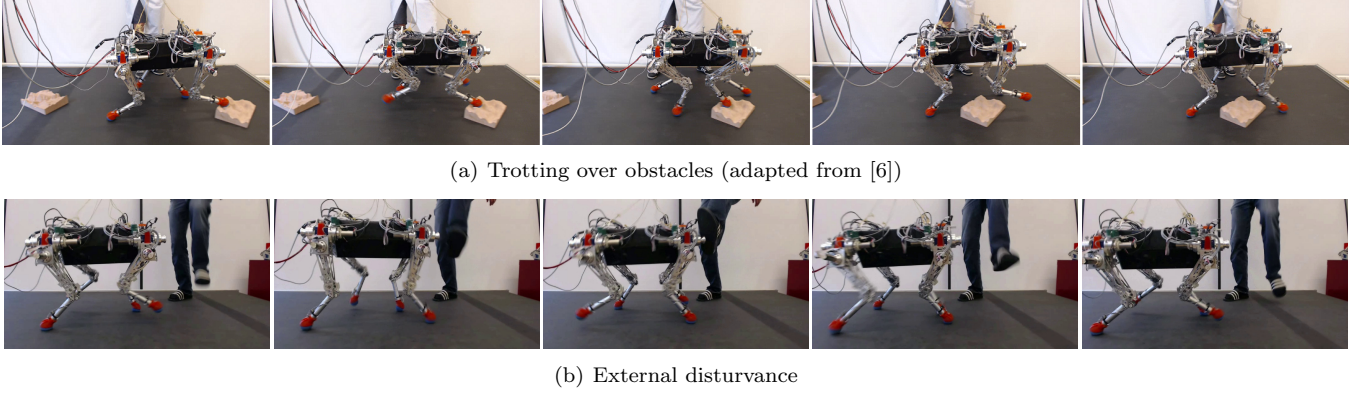


Figure 5: Robust dynamic trotting in 3D under significant external disturbances such as obstacles (a) or a kick (b).

motor controller ($\eta_{EPOS} = 94\%$), motor ($\eta_{mot} = 90\%$), and gearbox ($\eta_{HD} = 75\%$). In particular motor and gearbox efficiencies are significantly lower while walking due to the alternating load direction in every joint.

5 Discussion

In this project, we showcased the applicability of compliant actuation for torque controllable legged devices that can robustly perform different gaits from static climbing in challenging terrain to dynamic trotting. We see a large potential in this actuation principle for legged robots, in particular since the underlying principles are very similar to the muscular tendon system of humans and animals. We revealed in earlier studies that the applied series elastic actuators indeed largely support the passive dynamics of locomotion [10]. We showed that more than 60% of the energy can be passively stored and released while the motors only compensate for the energy loss. Furthermore, the output power and speed of the motor is amplified by a factor four. All these findings show an astonishing level of agreement with biomechanical studies (e.g. [15]).

We are also not that far away from nature in terms of efficiency. A similar sized dog (*canis familiaris*, 18kg) requires for the same locomotion speed a metabolic COT of 0.73 [16]. At first glance, this seems to be an extreme difference. However, considering that motors produce an average mechanical power of about 32W (COT=0.32), there is large potential to optimize the energy consumption of the electronic equipment. Ongoing progress in this field can potentially fully close this discrepancy with respect to efficiency. Comparing only the actuator performance with the biological counterparts unveils that our machines have for instance higher power and torque density (e.g. [7]) as well as a higher control bandwidth than human reflexes (e.g. [5]).

Despite these local advantages, animals still largely outperform our robots and there remains many unanswered research questions before our robots can compete with nature.

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